JAN 25 2007

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 20-09-2006	**2. REPORT TYPE** MAJOR REPORT	**3. DATES COVERED** *(From - To)*
4. TITLE AND SUBTITLE A LOW-COST FEMTOSATELLITE TO ENABLE DISTRIBUTED SPACE MISSIONS.	**5a. CONTRACT NUMBER**	
	5b. GRANT NUMBER	
	5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) MAJ BARNHART DAVID J	**5d. PROJECT NUMBER**	
	5e. TASK NUMBER	
	5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) UNIVERSITY OF SURREY	**8. PERFORMING ORGANIZATION REPORT NUMBER** CI07-0023	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) THE DEPARTMENT OF THE AIR FORCE AFIT/ENEL, BLDG 16 2275 D STREET WPAFB OH 45433	**10. SPONSOR/MONITOR'S ACRONYM(S)**	
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)	

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unlimited distribution
In Accordance With AFI 35-205/AFIT Sup 1

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
				15	**19b. TELEPHONE NUMBER** *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

IAC-06-B5.6.06

A LOW-COST FEMTOSATELLITE TO ENABLE DISTRIBUTED SPACE MISSIONS

Author:
Major David J. Barnhart, USAF, david.barnhart@ieee.org
Surrey Space Center, University of Surrey, United Kingdom

Co-Authors:
Dr. Tanya Vladimirova, t.vladimirova@surrey.ac.uk
Surrey Space Center, University of Surrey, United Kingdom
Dr. Adam M. Baker, a.baker@sstl.co.uk
Surrey Satellite Technology Limited, United Kingdom

ABSTRACT

A new class of distributed space missions is emerging which requires hundreds to thousands of satellites for real-time, distributed, multi-point sensing to accomplish long-awaited remote sensing and science objectives. These missions, stymied by the lack of a low-cost mass-producible solution, can become reality by merging the concepts of distributed satellite systems and terrestrial wireless sensor networks. However, unlike terrestrial sensor nodes, space-based nodes must survive unique environmental hazards while undergoing complex orbital dynamics. A novel sub-kilogram very small satellite design is needed to meet these requirements. Sub-kilogram satellite concepts are developing elsewhere, such as traditional picosatellites and microengineered aerospace systems. Although viable technical solutions, these technologies currently come at a high cost due to their reliance on high-density technology or custom manufacturing processes. While evaluating these technologies, two untapped technology areas became evident that uniquely encompass low cost and mass producibility by leveraging existing commercial production techniques: satellite-on-a-chip and satellite-on-a printed-circuit-board. This paper focuses on the design, build, and test results of a prototype satellite-on-a printed-circuit-board with a prototype unit cost of only $300. The paper concludes with mission applications and future direction.

1. INTRODUCTION

A new class of distributed space missions (DSMs) is emerging which requires hundreds to thousands of satellites for real-time, distributed, multi-point sensing to accomplish long-awaited remote sensing and science objectives. These missions, stymied by the lack of a low-cost mass-producible solution, can become reality by merging the concepts of distributed satellite systems (DSSs) and terrestrial wireless sensor networks (WSNs) [1]. However, unlike terrestrial sensor nodes, space-based nodes must survive unique environmental hazards while undergoing complex orbital dynamics. We believe that a novel very small satellite (VSS) design can fulfill these requirements. In this paper, we define a VSS as having a mass less than one kilogram.

Sub-kilogram satellite concepts, such as traditional picosatellites and microengineered aerospace systems have been around for some time. Although viable technical solutions, they come at a high cost due to labor-intensive or custom manufacturing processes. While evaluating the potential design space, two untapped technology areas were discovered that uniquely encompass low cost and mass producibility by leveraging existing commercial production techniques: satellite-on-a-chip and satellite-on-a-printed circuit board (satellite-on-a-PCB). The initial results of SpaceChip, which is a monolithic "satellite-on-a-chip" based on commercial CMOS technology, was first presented in [2] and updated in [3].

This paper focuses on the design, build, and test results of a prototype satellite-on-a-PCB. It is presented in a problem-solution format where the "problem" is the emerging set DSMs where real-time, distributed, multi-point sensing is required to accomplish long-awaited remote sensing and science objectives. The solution space of low-cost mass-producible VSS technologies is then discussed where a promising solution of satellite-on-a-PCB was discovered. The design, build, and test results of the prototype are presented. Mission applications, challenges, and future direction of the work are then discussed. .

2. DISTRIBUTED SPACE MISSIONS

The interchangeable terms, *distributed satellite system* and *distributed space system*, evoke the promise of realizing missions that have not been previously possible, while the term *constellation* is associated with a simpler form of the DSS concept. Jilla defines a DSS simply as "a system of multiple satellites designed to work in a coordinated fashion to perform a mission" [4]. Burns considers a DSS to be "an end-to-end system including two or more space vehicles and a cooperative infrastructure for science measurement, data acquisition, processing, analysis, and distribution" [5]. We find that Shaw offers the most complete definition [6] identifying two formal types of DSSs. The first type relates to system implementations where multiple satellites are sparsely distributed as a traditional constellation in order to meet various mission requirements. Constellation scenarios do not typically require precise orientation between spacecraft but optionally may require propulsive stationkeeping. Satellites in the constellation are usually linked via ground relays and systems. More recently, crosslinks, sometimes referred to as inter-satellite links, have enabled higher interconnectivity and to a limited degree, autonomy.

The second DSS type proposed by Shaw [6] introduces the concept of a local cluster, where satellites are intentionally placed close together in the same orbit to train on a common target. Optionally, this cluster of satellites may have a more complex instantiation, namely a formation. Formation flying requires that satellites in a cluster maintain precise spacing and orientation relative to each other, with the level of precision based on mission requirements. This directly implies that the spacecraft must have exact real-time location knowledge of all nodes and a propulsion system to maintain the formation. Formations cannot naturally exist in orbit very long before orbital perturbations disturb the arrangement. The motivation for formation flying is to synthesize an aperture, antenna, or some other sensor suite to achieve mission performance levels that cannot be currently reached by the largest single satellite. To date, most aspects of this concept have been widely studied, but the first implementation has yet to be realized, with the exception of a few initial experiments discussed later.

We divide DSSs into two classes - constellation and cluster, as shown in Figure 1; based on predominant characteristics and previous publications [4]-[6]. These two classes are not meant to be mutually exclusive. For example, a formation-flying cluster inherently requires crosslinks. To the best of the author's knowledge, all of the DSSs to date have been constellations utilizing ground links, with the exception of IRIDIUM and MILSTAR as will be discussed. Popular terms, such as *swarm*, are often misused in the literature due to multiple meanings and uses. Due to the lack of consensus, this term is not part of the classification diagram in Figure 1.

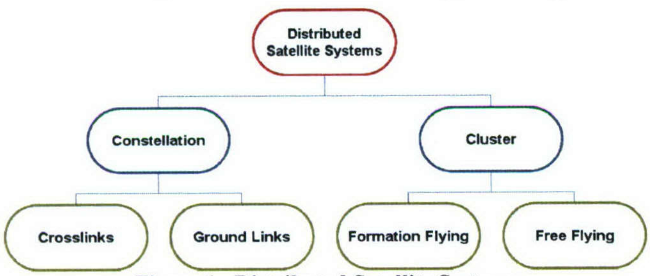

Figure 1. Distributed Satellite Systems

2.1 Current Distributed Satellite Systems

Here we present current DSSs grouped in the four typical mission categories: communications, navigation, remote sensing, and science, which includes space exploration.

Garrison summarizes the first, largest, and best example to date of a constellation utilizing crosslinks: the $5 billion IRIDIUM global mobile phone communications system launched in 1997 [7]. IRIDIUM is a constellation of 66 satellites, each weighing 689 kg, which provides global telecommunications services with very low latency to users with compact handsets. IRIDIUM is also one of the first DSSs with some degree of autonomy. Peters focuses on the fact that IRIDIUM is the only commercial system to date that employs RF crosslinks [8]. Although everyone realizes the phenomenal advantages of crosslinks, their high cost and complexity have discouraged any new systems from being fielded, with the exception of the U.S. military's $10 billion MILSTAR system.

Users worldwide currently enjoy free use of the U.S. Air Force Global Positioning System (GPS) constellation. The constellation is composed of 24 satellites in semi-synchronous orbits, placed evenly in six planes designed to provide position and timing information to users on land, sea, air, and now space. The system costs $400 million annually to operate and sustain. The Russians operate a similar system called GLONASS that utilizes 12 to 14 satellites in two planes. The European Union recently funded and launched the $36 million, 660 kg GIOVE-A technology pathfinder mission to support the development of Galileo.

Commercial imagery applications, where satellites take visible and IR images of specific regions of interest in the world are also widespread. Commercial imagery is used for mapping, agricultural data, disaster monitoring, and other requirements. Systems such as QuickBird, OrbView, IKONOS, SPOT, and Landsat offer resolutions up to 0.6 meters and are all classified as medium to large satellites. None of these systems qualifies as a DSS, as they are all single-satellite systems. Some recent consolidation in the industry has enabled the claim of a new imaging constellation, although not originally designed to be.

Small satellites have recently entered the Earth observation market. The Disaster Monitoring Constellation (DMC) developed by Surrey Satellite Technology Ltd. (SSTL) is composed of five $8 million, 166 kg Earth-imaging satellites. DMC offers an unprecedented revisit time of 24 hours, versus days or weeks from other commercially available imaging systems [9]. DMC is considered the first Earth imaging constellation.

NASA manages an ongoing program called the Earth Observation System (EOS), which currently coordinates 17 satellites performing various types of remote sensing and science missions with a few international partners, including the European Space Agency (ESA). The segment of EOS most interesting to this research is referred to as the "A-train," which is a set of six satellites in the same 705 km sun-synchronous orbit. Of those, PARASOL, CALIPSO, CloudSat, and Aqua are closely spaced, with the smallest distance being 100 km between CALIPSO and CloudSat [10].

The $130 million Space Technology 5 (ST5) program, launched on March 22, 2006, is a part of NASA's New Millennium Program [11]. The three-satellite constellation, each with a mass of 25 kg, was designed to evaluate technologies that can be used in future missions, mainly for space weather. Fong presents the $55 million FORMOSAT-3/COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) program, launched on April 14, 2006, which is an international collaboration between Taiwan and the U. S. [12]. COSMIC is a constellation of six satellites, where each spacecraft is 69 kg and carries three experiments: GPS occultation, tri-band beacon, and an ionospheric photometer.

2.2 Emerging Distributed Satellite Systems

There has been a literary explosion of DSS related topics in the past ten years. For example, the terms *distributed satellite systems*, *satellite formation flying*, and *satellite cluster* have become very hot topics in publications of the American Institute of Aeronautics and Astronautics (AIAA), as highlighted in Table 1. The term *satellite cluster* is a surprisingly old phrase which originally described placing communication satellites at very close distances in Geostationary orbit (GEO) to address the crowding issue or provide more capacity.

Year	"Distributed Satellite Systems"	"Satellite Formation Flying"	"Satellite Cluster"
<1991	0	0	19
1991-1995	0	0	9
1996-2000	5	16	23
2001-2006	33	82	82
Total	**38**	**98**	**133**

Table 1. DSS Terms in AIAA Publications

With the IRIDIUM, Globalstar, and ORBCOMM constellations in their current state of poor financial health with no relief in sight, Ashford notes that current realities have shattered all the previous predictions of a boom in low Earth orbit (LEO) based communications DSMs [13]. Norris has proposed that clusters of small satellites operating in LEO will eventually be used to "virtually" replace larger monolithic telecommunication satellites [14]. There may be a demand for this someday as the GEO belt fills up, especially over the most populated areas of the Earth. Another variant of this idea, put forth by Edery-Guirardo, is to augment larger satellite missions with a constellation of smaller communication relay satellites [15]. For the time being, large satellites in GEO appear to be the mainstay of high-bandwidth global communications.

One notable large-scale DSS for communication that never materialized was Teledesic. With conceptual designs ranging up to 840 satellites, Teledesic was to provide the first global "internet in the sky." The goal cost per satellite was about $5 million. The Teledesic idea was abandoned mainly due to predictions of poor financial results.

The GPS, GLONASS, and up and coming Galileo mission have already been categorized above as constellations using ground links. Nowhere in the literature has anyone proposed using crosslinks or a cluster for navigation DSSs. In addition, current navigation systems have known vulnerabilities to jamming [16]. For the GPS system in particular, next generation systems will mitigate this vulnerability with the combination of higher power RF signals with other anti-jam technologies, causing the mass to rise from the current 1,000 kg to an estimated 1,500 kg. The jamming environment will only get worse, requiring increased RF power from space. This trend does not facilitate the use of microsatellites or smaller systems.

There are numerous envisioned remote sensing DSSs; however, none of them has gone beyond the conceptual or experimentation phase. Examples of missions, which require real-time, distributed, multi-point sensing, are listed below. The mission ideas are based on the literature and suggestions formulated by the Surrey Space Centre (SSC) and SSTL.

- Volcano, fire, or Earthquake pre-emptive warning and detection
- Treaty monitoring (Kyoto Protocol, frequency, nuclear, other)
- Distress beacon monitoring
- Space control, signal intelligence, and other military missions [17]
- In particular imaging with frequent temporal repeats and high spatial resolution
- Constellation sharing where contributing members access the services of the entire group
- Disposable, short-lived rapid-response sensor networks for use in LEO and the upper atmosphere [18]

Reconfigurability of the satellite nodes would be required for more advanced missions, such as:

- Beam forming to remotely sense a particular location at optical or radio wavelengths
- Minimize power expenditure by dynamically optimizing the RF link

The TechSat 21 idea, led by Das, is arguably the pathfinder technology proposal suggesting a formation flying cluster could be used for a mission such as space based radar [19]. Similarly, multistatic radar may also be possible. Clusters of co-orbiting assistants/inspectors of larger satellites, the space shuttle, or the International Space Station (ISS) are suggested by Macke [20].

Science and exploration missions have traditionally been dominated by single-spacecraft or interplanetary probe missions due to characteristically limited science budgets and resources. There are a number of missions that are only now being envisioned as possible, due to the emergence of small satellites during the past couple of decades. Examples of missions that require real-time, distributed, multi-point sensing are listed below, where only those mission ideas that require a constellation of hundreds or thousands of low-cost mass-producible satellite nodes are referenced.

- Magnetotail behavior, solar wind variations, and other Geospace science [21]
- Interplanetary exploration based on satellite-on-a-chip [22]
- Monitoring and warning of large area space phenomena, mainly space weather, including plasma and radiation density [23]
- Monitoring wide-area highly time dependant phenomena, such as drag or Aurora
- Detailed characterization of environments to support interplanetary exploration, such as Mars, asteroids, or other planets
- Upper atmosphere monitoring, e.g. CO_2 levels at 60-250 km

Reconfigurability of the satellite nodes would also be required for more advanced missions, for example:

- Measuring ion or electron scale space weather events and effect within the magnetosphere (10s of meters to km's)
- Compensating for interference from other sources such as radiation (lightning, trapped radiation e.g. South Atlantic Anomaly, stray electromagnetic fields) by frequency hopping

There is only one serious DSS cluster proposal for science and exploration that is currently being developed: NASA's Terrestrial Planet Finder (TPF) mission [24]. TPF will rely on a formation flying cluster at one of the Sun-Earth libration points to synthesize a very large aperture to see further in the universe than ever before.

A simpler cluster mission proposed back in 2000 is to measure magnetic field variations around a spacecraft or perform visual inspection of the exterior for signs of damage. In addition, asteroid mapping and in-flight calibration of a communications beam pattern was suggested for clusters as well [21]. In 2001, the Orion-Emerald mission was proposed which would demonstrate a cluster of three formation flying satellites [25]. No reports of mission launch or success can be located. The mission was due to fly in 2003 on the Space Shuttle. The mission concept has not re-emerged in the literature after the Columbia tragedy.

Overall, the problem of formation flying is very complex. Carpenter has outlined all the challenges associated with realizing formation flight [26]. Fully appreciating the magnitude of this problem, the focus of this research has been on DSMs based on constellations that require hundreds to thousands of satellites for real-time, distributed, multi-point sensing to accomplish long-awaited remote sensing and science objectives.

3. VERY SMALL SATELLITES

Since the dawn of the space age in 1957, increasing mission requirements have driven up satellite mass from Sputnik's 84 kg to over 6,000 kg for some systems today. Consequently, cost, complexity, program timelines, and management overhead have grown considerably.

Reversing this trend, a fast-growing small satellite industry, rooted in academia, has enabled increasingly capable and cost-effective space missions. Focusing on sub-500 kg satellites, their success is based on embracing smartly reduced requirements, integrating commercial technology, streamlining management structures, and using efficient engineering practices. In order to compare the capabilities of satellites, the space community in general has developed mass classifications as shown in Table 2 [27]. Mission costs are also listed, approximated by the author. The preponderance of missions has been in the minisatellite and microsatellite ranges as shown in Figure 2 [27].

Table 2. Satellite Categories by Mass and Approximate Costs

Large satellite	>1000 kg	\$0.1-2B
Medium satellite	500-1000 kg	\$50-100M
Minisatellite	100 - 500 kg	\$10-50M
Microsatellite	10 - 100 kg	\$2-10M
Nanosatellite	1 - 10 kg	\$0.2-2M
Picosatellite	100 g - 1 kg	\$20-200K
Femtosatellite	1 - 100 g	\$100-20,000

Although minisatellites and microsatellites represent the largest segment of small satellite missions as just shown in Figure 2, this research is focused on the downward trend from nanosatellites to picosatellites to femtosatellites. Some have even humorously suggested a zeptosatellite class, which would be less than one gram. Looking closer, a mass histogram over the past 15 years of sub-10 kg missions is given in Figure 3 [27].

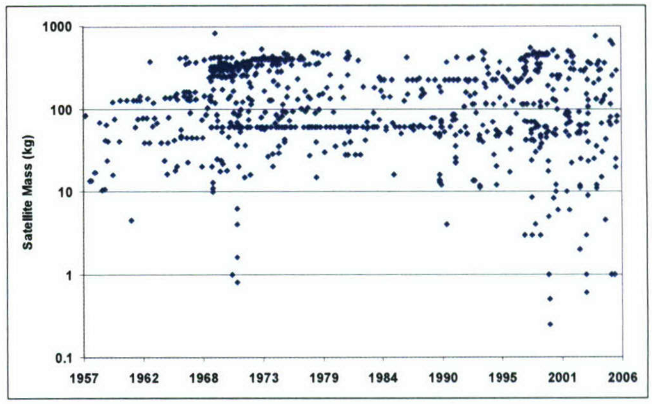

Figure 2. Small Satellite Mass Histogram

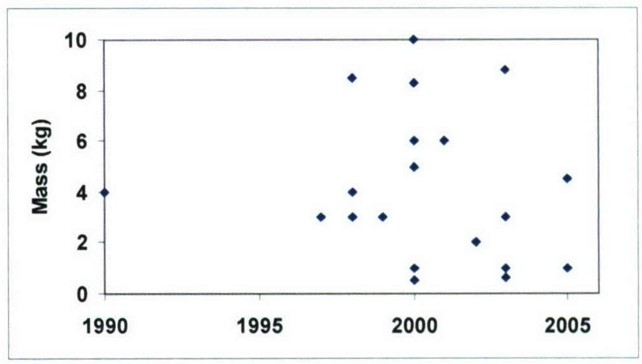

Figure 3. Very Small Satellite Mass Histogram

3.1 Nanosatellites

Although not included in the sub-kilogram VSS classification developed in this work, it is important to understand the capabilities and level of research in the nearest neighboring category of nanosatellites. As shown in Figure 3, over a dozen nanosatellites have flown in the past 15 years. They have all performed science or academic missions. The most capable nanosatellite flown to date was the \$2 million SNAP-1 mission back in 2000 with a mass of 6.5 kg. Designed and built by SSTL in only nine months, it was the first nanosatellite to demonstrate the complete set of satellite functions typically found in larger satellites, including full attitude and orbit determination and control [28].

There are two notable recent and ongoing nanosatellite concepts. The first one is the recently renamed MicroLink-1 effort [29]-[30]. MicroLink-1 was originally envisioned at Uppsala University in Sweden and now is being further developed by a spin-off company, Ångstöm Aerospace Corporation. They have invested heavily in the development of a custom multi-chip module (MCM) concept to build multifunctional modules, which is discussed further in Section 3.4.

The other nanosatellite concept of note is an ongoing feasibility study, funded by ESA, titled "Nanosatellite Beacons for Space Weather Monitoring." The interim report did not give any details of a conceptual design or approximate costs, other than a 6 kg reference mission flown in 2000 [31]. Although only a concept study, the members of the submitting team have a strong space industry record and are capable of mass producing nanosatellites.

3.2 Picosatellites

Sixteen picosatellites have flown in the past ten years. The first picosatellites mission flew in 2000, which was dubbed the Orbiting Picosatellite Activated Launcher (OPAL) [32]. Eight custom-built picosatellites were deployed, but only Picosat 1 & 2 were functional. The working pair was a Defense Advanced Research Project Agency (DARPA) mission to investigate picosatellites. They carried small experiments powered by a primary battery and successfully transmitted their data to Earth. They were tethered together and were considered one space object. Later in 2000, a second pair of DARPA picosatellites (Picosat 7 & 8) were supposed to be jettisoned from the MightySat host satellite, but no data has been found on the mission status.

The last eight picosatellite missions were "CubeSats," which is a university student satellite standard defined by Stanford University and California Polytechnic Institute. CubeSats are now available as a commercial kit that gives students a basic structure and flight computer for about $5,000. The design concept is simply a scaled-down version of larger satellite designs using miniaturized modules. The payload and all other subsystems must be supplied by the user, usually resulting in an average total cost of $40,000. New companies are emerging to supply the CubeSat market, such as Clyde Space, who now provides electrical power subsystems [33]. In 2003, the Eurockot launch deployed the first five CubeSats, but only three were declared successful. Again, in 2005, the SSETI Express deployed three more CubeSats, with two being successful. Overall, picosatellites have a 50% success rate. These missions are summarized in Table 3. Unfortunately, 14 new CubeSat missions were destroyed by a launch vehicle failure in July 2006.

Table 3. Summary of All Picosatellite Missions to Date

Mission	Satellite	Bus	Status
OPAL 2000	Picosat 1 & 2	Custom	Success
	Thelma	Custom	Failed
	Louise	Custom	Failed
	JAK	Custom	Failed
	Stensat	Custom	Failed
MightySat 2000	Picosat 7 & 8	Custom	Status Unknown
Eurockot 2003	CubeSat-XI-IV	CubeSat	Success
	DTUSat	CubeSat	Failed/Unknown
	CUTE-I	CubeSat	Success
	CanX-1	CubeSat	Failed/Unknown
	AAU CubeSat	CubeSat	Short Life/Power
SSETI 2005	CubeSat XI-V	CubeSat	Success
	UWE-1	CubeSat	Success
	Ncube-2	CubeSat	Failed/Unknown

One notable picosatellite that has been in development at SSC since the success of the SNAP-1 nanosatellite is PalmSat [34]. PalmSat is an independent design from CubeSat and hopes to offer more capability with deployable solar arrays. It is configured for single-ship missions focused on science, with the possibility of operating in a distributed environment. Its development is currently advanced by students' research projects.

3.3 Femtosatellites

To date, no femtosatellite has ever been launched into space. Cyrospace claims to have designed a femtosatellite, but attempts by the author in contacting the company or identify published documentation have turned up negative [35]. Helvajian and Janson have orchestrated a femtosatellite design for spacecraft inspection based on Microelectromechanical Systems (MEMS) and micromachining of glass in 2002 [36]. This particular femtosatellite design focuses on propulsion and structure as detailed in Section 3.4, but they have yet to publish a complete solution.

3.4 Emerging Very Small Satellite Fabrication Technologies

An emerging femtosatellite concept that has been discussed in the literature is satellite-on-a-chip. The first mention of satellite-on-a-chip was in 1994 [37]. Over twenty references in the literature have used this term, but no serious effort has been undertaken to pursue the idea until 2005 when the author first proposed the SpaceChip concept [2].

The aim of the SpaceChip project is to implement a monolithic "satellite-on-a-chip" using commercial CMOS technology. The undertaken conceptual design showed that a unit cost of less than $1000 could be achieved, which is supported by more than twenty references to recent work that directly support the SpaceChip idea. The conclusion from this work is that such an approach although entirely possible, is limited by the current on-chip antennas technology, achieving a very short communication range of only 5 m [3].

During the process of designing SpaceChip, a risk-reduction strategy of developing a printed circuit board (PCB) prototype of a femtosatellite or satellite-on-a-PCB was accomplished in parallel. The original purpose of this approach was to develop the architecture by integrating single-chip solutions for the payload and subsystems on a PCB. As the design emerged, its capabilities have already shown that they can potentially enable a class of missions that require real-time, distributed, multipoint sensing. In addition, the concept relies nearly entirely on commercially available components, PCB manufacturing, and assembly yielding a prototype unit cost of $300 as detailed in Section 4.

Since 1998, Helvajian and Janson both working for the Aerospace Corporation, El Segundo, California, have pioneered the idea of microengineering of aerospace systems [38]-[39] and have published several recent works on various VSS concepts based on MEMS [40]. One of the earliest approaches was an "all silicon" design, where the satellite is constructed with miniature components [41]. While Janson only touches on leveraging CMOS technology [42], he has strongly supported the upcoming emergence of technologies specifically targeted at developing VSSs [43]. A notable development is the satellite inspector concept, proposed initially with a 100 g mass baseline [36], but the concept has been recently revised, giving it a mass above 100 g, but still below one kilogram [44]. This proposal is mostly focused on propulsion and structure, briefly addressing the other required subsystems. A recent informal discussion with Aerospace revealed that their target cost per satellite is $10,000 and that they envision a 200-hour manufacturing time per satellite.

Around the same time Xuwen and later Shul, published similar concepts, but no follow-on effort has emerged [45]-[46]. In parallel to that, the concept of multifunctional structures and architectures started to emerge backing the idea

of mass production of very low cost VSSs [47]. This approach fostered the responsive space movement [48] proposing that satellite systems could be built and deployed very rapidly based on leveraging streamlined manufacturing processes and modular technologies [49].

Bruhn of the Ångström Aerospace Corporation has also led an effort to leverage the MEMS concept to design of multifunctional modules specifically for aerospace applications [29]-[30]. The goal is to reduce satellite mass and volume by "orders of magnitude" by introducing a new architecture called Multifunctional Micro Systems (MMS), enabling new nanosatellites that have the capability of present-date microsatellites. MMS is based on module re-use and parallel operation. Recently, their technology was licensed by the newly formed CANEUS NPS (nano-pico-satellite) Inc., which aims to mass-produce nanosatellites for $4 million and picosatellites for $2 million within three years [50].

3.5 Complexity Versus Cost Comparison of VSS Approaches

In summary, VSS technology options to date are very limited. The first picosatellites used unique satellite busses, with a failure rate of 50%, until the CubeSat standard was developed. CubeSat has addressed some important issues by reducing the complexity of satellite design, by offering a common structural configuration, data handling subsystem, and launch vehicle separation system [51]. However, users must still custom develop their own payload and subsystems to build a working satellite, which is a labor-intensive process and approaches a total cost of $40,000 on average. In addition, the CubeSat approach has not improved the picosatellite failure rate, which is still 50% overall. Due to the recent destruction upon launch of 14 CubeSats, we will not know if their success rate has improved. There is another planned launch of seven CubeSats in September 2006.

Microengineered aerospace systems, in development by the Aerospace Corporation in the U.S. and similarly at the Ångström Aerospace Corporation of Sweden, offer the potential of very high technology density. However, neither entity has yet produced a complete flyable VSS solution. Realizing that they are developing and depending on custom fabrication processes, their solutions will mostly likely prove to be very expensive [50].

Figure 4 compares the relative complexity vs. cost of the four technology areas discussed.

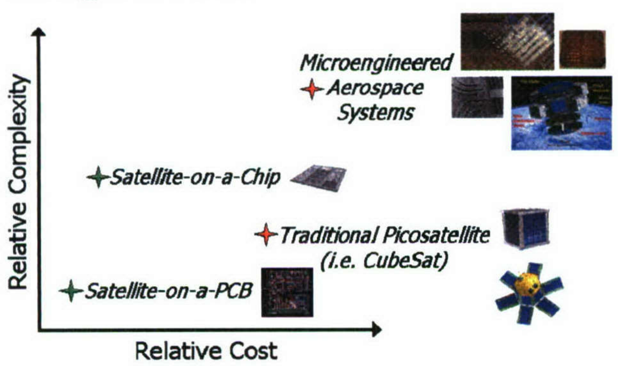

Figure 4. Very Small Satellite Complexity vs. Cost Comparison

4. SATELLITE-ON-A-PCB DESIGN

Seeing that the available high-cost technologies rely on labor-intensive or custom manufacturing processing, the author initially investigated the satellite-on-a-chip approach, which leverages the commercial availability of CMOS foundries. While this technology is still considered worthwhile to pursue, SpaceChip's range of applications has proved to be very limited, even with a unit cost of only $1000.

In parallel to the SpaceChip feasibility study [2]-[3], a rapid PCB prototype of a femtosatellite was envisioned to help guide the SpaceChip architecture. As the goal was to determine how much satellite capability could be realized in a 100 g package, the research was aimed at addressing the system architecture and basic capabilities. Many of the challenges of the space environment and mission architecture have yet to be met as discussed in Section 7. This project has great novelty in itself, as a fully functional femtosatellite has never been realized until now.

The author's experience as the team lead and one of the designers of EyasSAT inspired the idea [52]-[54]. EyasSAT is a 2.5 kg modular, expandable educational satellite system that facilitates hands-on teaching and learning of satellite systems engineering in a classroom environment. EyasSAT is currently in the U.S. "Patent Pending" status. The project name of ES-Femto was coined for the satellite-on-a-PCB design, merging the two ideas. ES-Femto is a completely new design and therefore does not contain any of the patent pending intellectual property of EyasSAT. The two main goals for the project are to:

- Guide the SpaceChip architecture design by prototyping with commercial components
- Function as a complete standalone femtosatellite that could be space qualified

During the design process, three spin-off goals were realized:

- Offer a payload module option for EyasSAT
- Experiment with improvements for the next EyasSAT design
- Function as a reduced-capability low-cost alternative to EyasSAT

4.1 System Description

The goal of the ES-Femto design is to determine what capabilities can be realized in a 100 g femtosatellite with commercial components and fabrication technologies. The system requirements mirror those for SpaceChip—the envisioned mission architecture would be a dispersed constellation of femtosatellites operating as a DSS to provide the capability for real-time, simultaneous, multipoint sensing. Similar to SpaceChip, Space Mission Analysis and Design principles were used throughout the design of ES-Femto [55]. However, the ES-Femto design was a "bottom's up" approach, where a finite set of payload and subsystem components were integrated to determine the overall system capability, which in turn, determined it's range of applications.

The design process became fairly simple by imposing a few constraints for simplicity:

- Use familiar Atmel, Dallas, and Maxim IC products
- Use surface-mount components as much as possible
- Maintain EyasSAT compatibility by using the PC104 form factor and EyaBUS standard, which defines the data and power interface

After two design revisions, a final system configuration was reached. The basic outline follows with key components:

Payload
- 640x480 CMOS imager (ST Microelectronics VS6502)

Configuration and Structure
- Mass less than 100 g
- Single 4-layer PCB measuring 9.0x9.5 cm (PC104 standard)
- Module function determined by component population

Electrical Power Subsystem (EPS)
- 7-cell solar array using $5 silicon hobby cells
- Peak power tracking (PPT) circuit (MAX856/982)
- 645 mAh Lithium-Ion battery
- Battery charge regulator (BCR) (MAX856/982)
- Regulated 3.3V system power supply (MAX604)
- Telemetry: voltage and current measurements for battery, solar array, and power supply (MAX471), and separation

Data Handling (DH)
- Reduced instruction set (RISC) microcontroller running at the minimum frequency to support 115.2 kbps data rates (Atmel Mega128L, 3.3V, 4 MHz, 128K flash, 4K SRAM)
- CMOS-level umbilical (Acroname USB CMOS converter)
- In-system programmable (Atmel AVRISP dongle)
- Serial peripheral interface (SPI) link for EyasSAT payload
- Telemetry: real-time clock with battery backup (DS1302Z)

Communication (Comm)
- 2.4 GHz, 60 mW RF ZigBee module (MaxStream XBee)
- Telemetry: received signal strength indication (RSSI)

Attitude and Orbit Determination and Control (AOCS)
- iTrax-03S single-module GPS receiver and Sarantel antenna
- Single-axis magnetorquer
- Telemetry: front and back "digital" (light/dark) sun sensors

Thermal
- Telemetry: solar cell and battery temperature

The computer-aided design (CAD) tool selected for this project was EAGLE from CadSoft. It is PC based, very inexpensive, easy to use, and has an extensive parts database. A good practice and interim step between the CAD design and fabrication is to visually inspect the final Gerber PCB layer files for errors with a viewer tool, such as Pentalogix Viewmate. The PCBs were then produced at a commercial facility in prototype quantities.

The selected payload is the ST Microelectronics VS6502 color CMOS imager with integrated lens. It has a two-wire (I^2C) control and 5-wire data interfaces. A picture of the device and basic specifications are shown in Figure 5. The device snaps into a surface-mount socket mounted on the PCB or at the end of a remote-cable for mounting on the top of the EyasSAT system when in payload configuration.

- 640x480 (VGA) pixel resolution
- 30 frames/sec video or still shots
- 5.6 μm x 5.6 μm pixel size
- 2.05 V/lux-s sensitivity
- +37 dB signal/noise ratio
- 2.6 to 3.6V supply voltage
- <30 mA current draw when active
- 0 to 40 °C operating temperature
- 11x9x6 mm package size
- 14 pad SmOP package
- 47° field of view, f#2.8

Figure 5. ST Microelectronics VS6502 CMOS Imager

The initial design of ES-Femto has been purposely confined to a single PC104 form factor configuration. Additional work in the next phase of research will focus on the entire scope of launch and space environment issues [56]. These are discussed in Section 7 of this paper.

Satellites are typically composed of numerous subsystems to support the payload. It is essential to have the following subsystems: EPS, DH, Comm, and thermal control. Optionally, mission and payload requirements may call for ADCS, OCS, and/or propulsion subsystems. The following sections discuss the initial design considerations for the required subsystems.

4.2 Electrical Power Subsystem

A spacecraft EPS is typically composed of four basic functions: power source, energy storage, power distribution, and power regulation and control [55]. The basic EPS design of ES-Femto is to utilize primary solar power, secondary rechargeable batteries, and deliver 3.3V regulated power.

Solar energy was the obvious choice for the primary power source. The most efficient hobby-grade solar cells that can be readily purchased are 15% Silicon (Si), measuring 2x4 cm. They have an advertised peak power output of 0.484V at 250–275 mA. The back side of the PC104 PCB is available for solar cell mounting. Leaving space for a few parts that require mounting through-holes (vias), only seven can be mounted.

To extract the maximum power out of the solar array, peak power tracking (PPT) was selected over the less complex, but inefficient direct energy transfer (DET) choice. This method places a smart interface between the solar array and battery to extract the maximum amount of power out of the solar array over a range of solar conditions. The baseline design was chosen from a Maxim application note on their website as shown in Figure 6 [57].

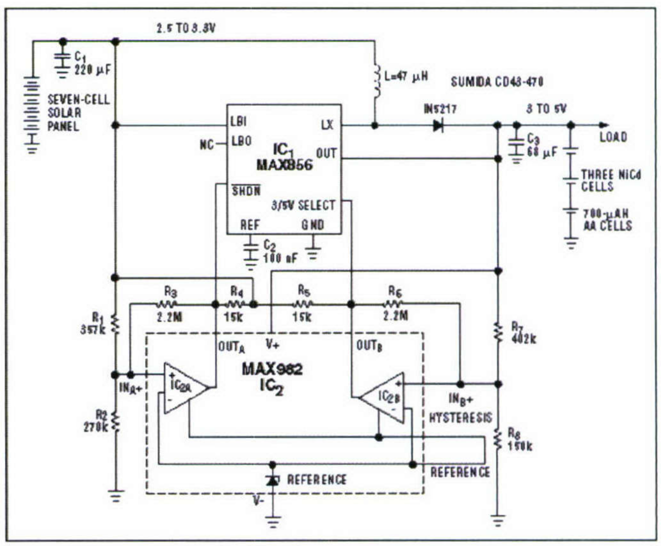

Figure 6. Maxim PPT and BCR Circuit

The Maxim design example suggests using an array of seven solar cells with the same specifications of the hobby-grade cells selected previously, which is a convenient coincidence. The principle of operation is simple. As charge from the solar

array builds up on C1, the voltage is monitored by one of the voltage comparators on the MAX982 IC (Fig.6). When the voltage reaches the threshold (2.9V), the MAX856 step-up DC-DC converter is powered up and converts the stored charge on C1 to 5V power, which is enough to charge the battery which has a nominal voltage of 3.6V. Although shown as nickel cadmium technology in Fig. 6, a Li-Ion battery will be used. When the voltage on C1 falls below the lower threshold (2.5V), the step-up converter is shut down. The cycle repeats and the battery is charged in pulses as long as there is solar energy.

A second important feature of an efficient EPS is battery charge regulation (BCR). The Maxim circuit implements a BCR very simply by using the second voltage comparator of the MAX982 IC to monitor the voltage level of the battery. When the battery charge reaches 4.6V, the MAX856 step-up converter is "shut down" by toggling the 3.3/5V line to 3.3, causing the battery to charge at 3.3V, which in effect renders the step-up converter ineffective, as the nominal battery voltage is 3.6V.

Selecting a suitable battery was surprisingly difficult due to the finite types of physical battery configurations. Originally, a 3.6V, 80 mAh nickel-metal hydride (NiMH) used for PC memory backup was chosen. It did not have enough capacity, so the higher density Li-Ion technology was chosen. A 645 mAh pack designed for a digital camera was chosen with the right dimensions.

The final major EPS component is power regulation. Efficient satellite EPS designs use DC-DC converters, which offer efficiencies greater than 90%. However, a MAX 604 linear regulator offers 92% efficiency when stepping down from 3.6V to 3.3V (3.3/3.6=92%).

Although not a major function, satellite EPS designs typically include a way to monitor the health and status of the system remotely, which is usually referred to as "telemetry." In this design, the most important telemetry points are the voltage and current of the solar array, battery, and the 3.3V regulated power supply. These telemetry points are inherently analog, so an analog-to-digital converter (ADC) is required, which is discussed in Section 4.3 on Data Handling. In order to sample the voltage, simple resistor-based voltage dividers are used to scale the voltage points down to the operating range of the ADC. To sample the current, a voltage drop must be measured across a very low resistance resistor and then amplified using an operational amplifier. An elegant packaged solution for this circuit is the MAX471, which was used in the latest ES-Femto design.

4.3 Data Handling Subsystem and Software Development

In order to leverage experience previously gained, the chosen heart of the DH subsystem was the Atmel Mega128 8-bit AVR® microcontroller. The 3.3V low-power Mega128L variant was selected for this project, with the key advantage being an advertised low current draw of less than 5 mA when operating at 3.6864 MHz. The Mega128L is in-system programmable (ISP), meaning that it can be programmed without having to be removed from the circuit. This is accomplished via a 6-wire programming interface to an AVRISP® dongle with is connected to an RS-232 or USB port of a computer. The key features are outlined in Figure 7.

- Low-power 3.3V variant
- Up to 8 MHz clock, 5 mA @ 4MHz
- ISP flash programmable
- Boot-loader programmable
- 128K flash memory
- 4K EEPROM and 4K SRAM
- I^2C interface
- 53 multipurpose I/O lines
- Six counters/PWMs
- 8-channel 10-bit ADC
- Dual USART interface
- SPI interface
- Low-power sleep modes

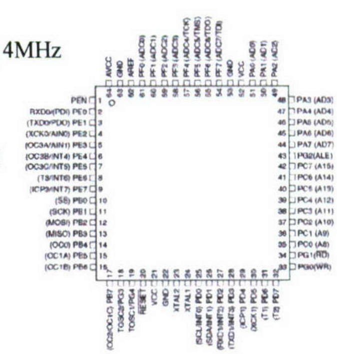

Figure 7. Atmel Mega128L Key Features

The I^2C interface is used to control the CMOS imager payload. Four of the I/O lines are configured as inputs to read the pixel data nibbles. One of the I/O lines is configured as a hardware interrupt to detect when pixel data is valid. Another I/O line is configured as a high-speed pulse-width modulator (PWM) to drive the system clock of the imager. A final I/O line to the imager can put it in lower power mode.

The eight ADC channels are used to read the EPS and Thermal telemetry. Two other I/O lines are configured appropriately to collect the separation status and percent PPT.

One Universal Synchronous-Asynchronous Receiver Transmitter (USART) port configured at 115.2 kbps is used either for a wired umbilical connection during development or to the XBee RF module. Four I/O lines control its state.

The other USART port configured at 4800 bps interfaces with the GPS module. Six additional I/O lines control its state. Three other I/O lines control the magnetorquer and read data from the sun sensors.

Finally, the serial peripheral interface (SPI) is used only when the system is used as an EyasSAT payload. MAX3371 level shifters are used on the four-wire SPI connection to link together the 3.3V and 5V systems.

The Mega128L has a generous 128K non-volatile flash memory space, which can be used for program and data storage. However, it is rated at 10,000 duty cycles, so using it for data storage should be kept to a minimum, as one read/write cycle counts as one duty cycle. 4K of non-volatile electrically erasable/programmable read only memory (EEPROM) and 4K of volatile static random access memory (RAM) is available for program use.

Software development for the project was relatively straightforward. CodeVisionAVR was selected as the software development environment, as it is one of the best tools on the market and has a large user base and support community. The software for the project was just over 1000 lines of code written in the ANSI C language, with most of those lines being comments. The compiled binary file is only six kilobytes in size, taking less than 10% of the available code space. Timers are used to run scheduled functions, such as telemetry reporting. Hardware interrupts are used to detect user commands or subsystem events and respond appropriately by running a subroutine.

4.4 Communications Subsystem

The ES-Femto Comm subsystem is one of the key elements of the design, as the communication capabilities will directly influence potential DSS constellation designs. The two main drivers are low-power long-range communications and unlicensed operations. Unlicensed operations can be achieved by operating in one of the Industrial, Scientific, and Medical (ISM) RF bands. The 2.4 GHz band was selected for this project, as it is legal to use in North America and Europe.

A single-chip RF solution was sought, as this mirrors the work that will take place with SpaceChip. The Atmel ATR2406 ISM Transceiver was used on the first revision of the PCB. Atmel provided excellent technical support, software examples, and an initial PCB layout. In the end, it required too many external components, the Micro Lead Frame (MLF)-type packaging was too hard to solder by hand, and the transmission range was found to be less than 100 m.

Two potential solutions emerged on the market after the first design was completed. The MaxStream XBee module is a ZigBee/IEEE 802.15.4 commercial integrated module. Two types are available, the low-power XBee and the high-power XBee Pro. The XBee Pro is the best option as it offers an improved electrical-to-RF transmission efficiency of 6.7% and a range of about one mile.

Although the mission architecture is not yet fully complete, it is well understood that satellites placed in orbit at only a one-mile separation will drift apart very quickly. For now, the XBee Pro will be used for this stage of the development. A radio with more range, such as the MaxStream XTend transceiver, has a terrestrial range of 30-40 miles and has a very high RF efficiency. Its potential use will be discussed at the end of the paper. A comparison of all four transceiver technologies is shown in Figure 8. Other similar products are now available on the market from other manufacturers.

Specification	ATR2406	XBee	XBee Pro	XTend
Vendor	Atmel	MaxStream	MaxStream	MaxStream
Cost	$8	$19	$32	$179
PCB area	3x6 cm	2.4x2.8 cm	2.4x3.3 cm	3.7x6.05 cm
Mass	1 g	3 g	4 g	18 g
Software required	50% CPU use	No	No	No
External parts	21 & custom PCB	0	0	0
Max data rate	122.88 kbps	115.2 kbps	115.2 bps	115.2 bps
RF Power	2.5 mW (4 dBm)	1 mW (0 dBm)	60 mW (18 dBm)	0.5 W (27 dBm)
Range	~300 m	258 m	1335 m	>50 km
Receive current	57 mA	50 mA	55 mA	80 mA
Transmit current	42 mA	45 mA	214 mA	600 mA
Transmit efficiency	1.3%	0.67%	6.7%	25.3%

Figure 8. Comparison of ISM Transceivers

4.5 Attitude and Orbit Determination and Control Subsystem

Due to the mass, size, and power constraints of the proposed design, very limited AOCS options were available for ES-Femto. For attitude determination, two cadmium sulfide (CdS) sensors, one on the front and the other on the back, are used to tell which face of the PCB is illuminated. For attitude control, a high-current p-type field-effect transistor (pFET) is used to power a magnetorquer coil, which is activated by one of the PWM channels, so its duty cycle can be adjusted.

The first PCB revision did not include any considerations for orbit determination and control (OCS). While evaluating potential mission applications, it became apparent that for many missions, a key enabler is to know where the satellite is when the potential payload collects data.

The obvious solution is a GPS receiver. Since the start of this project, two GPS modules that are small enough to fit on this design were introduced on the market. The Fastrax iTrax-03S and Trimble Copernicus are surface mount packages measuring less than 20x20x3mm only require an external antenna and filtered power. The Fastrax module was chosen as it was readily available through common distributors, while the release of the Trimble module has been delayed. Sarantel offers an excellent miniature passive surface mount antenna.

For actual space application, terrestrial GPS receivers, such as the Fastrax module cannot be used as-is in space. Due to the orbital velocity of about 7.5 km/s in low Earth orbit, the receiver firmware must be modified. This problem has been well documented and solutions reported on [58].

4.6 Thermal Control Subsystem

The thermal environment is one of the most challenging issues in spacecraft systems engineering. For the initial version, the thermal aspect of the space environment was not taken into account. However, to implement a minimal TCS, temperature telemetry points seemed to be most useful. Since six ADC ports are used by the EPS, two ports remained. The spacecraft components that are the most crucial to monitor for temperature are the solar array and battery.

5. ASSEMBLY, INTEGRATION, AND TEST RESULTS

The assembly of ES-Femto, was fairly straightforward. All components were hand-soldered by the author, with the exception of the GPS module, which required the help of a soldering technician. Satellite "integration" at this scale of design is inherent, as the entire spacecraft is on one PCB. Pictures of the second revision of ES-Femto are shown in Figure 9 and Figure 10.

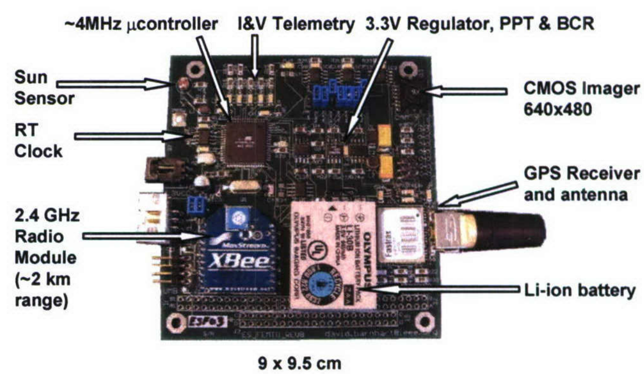

Figure 9. Front Side of ES-Femto

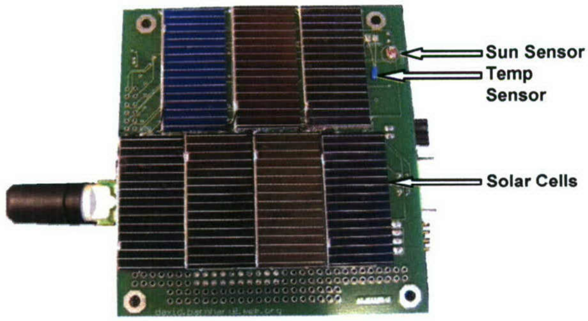

Figure 10. Back Side of ES-Femto

The first PCB design of ES-Femto did not allow for testability of all points without incrementally building it up. Applying that lesson learned, the second revision allows for isolation and testing of all subsystems on the PCB after it is completely populated with all parts.

Acceptance testing was limited to the inspection of the commercial parts and the custom PCB. Some parts were ordered early for a "paper-fit" on a to-scale printout of the PCB. When the PCB was received, it was compared to the printout and simple electrical tests were performed, mainly to ensure that the power and ground lines were not shorted, nor connected to any other important signal or power lines.

Functional testing and component characterization were performed on each component as appropriate. A summary of functional test results are given in Table 4.

Table 4. Functional Test Results in Order of Completion

Test	Expected	Measured/ Observed
GPS lock	45 sec	27 sec
CPU ISP programming	Pass	Pass
CPU clock frequency	3.6864 MHz	3.6857
UMB link to PC	Pass	Pass
CPU read GPS @ 4800 bps	Pass	Pass
EyasSAT SPI interface	Pass	Pass
RF comm link @ 115.2 kbps	Pass	Pass
RT clock frequency	32.768 kHz	32.742
RT clock backup	Pass	Pass
Thermistor readings (2)	Pass	Pass
Sun sensor readings (2)	Pass	Pass
Torque rod activation	Pass	Pass
EPS voltage regulation	3-5 V	3.29 V
EPS voltage telemetry (3)	Pass	Pass
EPS current telemetry (3)	Pass	Pass
Solar array output	0-3.39 V	Pass
EPS PPT	Pass	Pass
EPS BCR	Pass	Pass
CMOS Imager	Pass	Pass

The following sections summarize the testing and results of the payload and subsystems beyond functional testing. Some components required straightforward testing, basically checking if the circuit is functional, while others required a characterization over time or varying conditions.

5.1 Payload Test Results

The payload is the CMOS Imager. The imager was able to be switched on by command from the CPU. It was originally not clear from the documentation what clock frequency was needed by the imager. After experimenting with several values, it was found that a clock of 6 MHz was required. This was able to be provided by one of the high-speed PWM channels of the CPU. The imager must have a system clock to accept configuration commands on the I^2C bus and generate pixel data on the data bus. The imager was programmed to take a still image at 320x240 pixels. The current draw was 30 mA maximum during image capture.

5.2 Structure and Configuration Test Results

System mass is 70 g which is below the 100 g limit set for the project. Further structural development and testing is discussed in Section 7.

5.3 EPS Test Results

The EPS was heavily tested, as it has the most testable points of all the subsystems. Table 5 presents the results. The only significant deviation from the expected results is the operating point of the PPT/Solar Array as found in Figure 11. The logical explanation is that the expected results are based on a "one sun" test of the results which best approximates solar conditions, while the result found here was from an indoor test using a 500W halogen lamp, which is not full-spectrum. Even so, the EPS is able to deliver a maximum of 689 mW, when the average power requirement of the system is 220 mW at 3.3V (66.7 mA) as shown in Table 6.

Table 5. EPS Characterization Results

Test	Expected	Measured/ Observed
Regulator efficiency	92%	92%
PPT/BCR efficiency	80%	82.7%
PPT charge threshold	2.9V	2.95V
PPT drain threshold	2.5V	2.63V
PPT operating point	3.4V, 250 mA	2.6V, 265 mA

Table 6. ES-Femto Power Budget

Subsystem	Typical	Typical (mW)	Actual (mW)
Payload	40%	26	10
EPS	15%	10	1.3
DH	10%	7	18
Comm	30%	20	170
ADCS	5%	3.3	130
Total:	100%	86	52

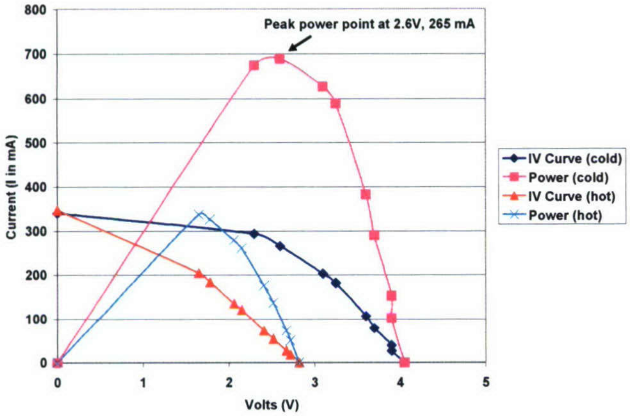

Figure 11. ES-Femto Solar Array IV Curve Results

As mentioned in the design section, the original battery used was an 80 mAh 3.3V NiMH battery, which was not sufficient. The Olympus Li-30B battery selected performed much better. Simulating a full system load in eclipse, the battery was fully charged then discharged at 55 mA. The battery was able to operate for about six hours before it reached the "knee," which is the rapid drop off point that no rechargeable battery technology is designed to operate in. The results are shown in Figure 12.

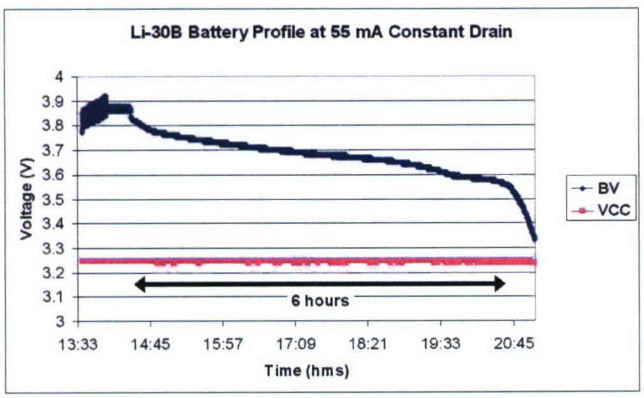

Figure 12. Li-Ion Battery Discharge Test

5.4 DH and Software Test Results

Beyond basic functional testing, the DH subsystem testing is mainly focused on the software. Because the characteristics of many of the hardware components are not known until they are interfaced with the CPU, only skeleton code was able to be written before a completed PCB was available. The first revision of the PCB allowed much of the software to be developed. The bulk of the code for the first revision was to support the ATR2406 transceiver, which required significant processor support. The XBee modules have their own CPU; so much of that software was eliminated. To enable progression of testing of subsystems, some of the software had to be developed during testing. The CPU draws 5 mA while running and there are multiple power saving modes that have not been implemented yet which will reduce the power.

5.5 Comm Test Results

The XBee Pro modules were used because of their higher RF output power. As advertised, they were able to stream data at 115.2 kbps. While receiving, they draw 170 mW. While transmitting, which is a very short amount of time, they draw 890 mW. The effective range in an open field is 1.5 km at the full output power setting of 100 mW RF.

5.6 AOCS Test Results

The attitude determination and control components was straightforward. Basic functionality of the sun sensors was all that was needed for the attitude determination. For attitude control, the torque rod current draw was measured at 100% duty cycle and was found to be 10 mA as designed.

The orbit determination component, which was the GPS module, required surprisingly little testing. Since it was the most significant addition to the second PCB revision, it was mounted and tested first even before the CPU or any other components were mounted. The reason for doing this was to establish a performance baseline before other potentially interfering components were installed.

The first test of the GPS module was a disappointment, as lock could not be achieved. After struggling to find the source of the problem, it was found that poor ground connections from the module to the PCB was the problem, as the module is sensitive to ground noise. After consulting with a soldering technician, the proper soldering technique was learned and applied. This resulted in the module achieving GPS lock from a cold start in 27 seconds, which is under the maximum advertised value of 45 seconds. While powered on, the GPS receiver drew 130 mW.

5.7 Thermal Test Results

The thermal subsystem was a functional test of the two thermistors. Testing also included calibration of the thermistors to set the telemetry coefficients in software. After calibration, the battery reached a steady state temperature of 25 °C during constant drain at a room temperature of about 23 °C. The solar array hot and cold tests used the results from the solar array thermistor.

6. CHALLENGES AND FUTURE DIRECTION

The next phase of the design will focus on a real space mission, discussed in the next section. For ES-Femto to operate in the space environment, a number of challenges need to now be addressed. If the project was initiated with spaceflight in mind, then the challenges of the space environment would have been incorporated earlier in the design phase. However, it is not too late to revise the design to address these challenges.

The space environment introduces unique problems for systems operating in space that are not ever encountered in a terrestrial environment. The upper atmosphere, debris, radiation, vacuum, and the orbit are all hazards that require specific design considerations. The upper atmosphere encountered in LEO, where ES-Femto will fly, will impact the system lifetime and differential drag on the nodes in the constellation.

Other debris in orbit is not necessarily a threat to ES-Femto, but the greatest criticism to date for missions requiring large number of satellites is *becoming debris*. The thought is to use

ES-Femto in missions that are very short-lived, so that the satellites will reenter with a few months after deployment.

Radiation and charged particles, whose fluence varies with altitude, is one of the main problems addressed when flying COTS components in space. Long-term exposure to radiation causes a degradation of performance and increased power draw due to the total ionizing dose effect, which will not be a concern for short-lived missions like ES-Femto will support. Single event upsets are the main issue.

The vacuum of space introduces unique thermal control challenges, as the convective heat transfer with the air in terrestrial environment mitigates non-space system thermal problems.

Finally, the orbital environment of freefall introduces more design considerations, for the spacecraft itself and the constellation. The set of proposed mission applications in the next section do not require any attitude control, but in general, it is desired to maintain some attitude control. Some simple techniques are possible to maintain attitude control where the requirements are not critical [59]. The other issue of orbits and all the natural perturbations is ensuring that the minimum distance between satellite nodes can be achieved. There are some proposed ways to control some orbital parameters using non-propulsive stationkeeping techniques [60].

6.1 MISSION APPLICATIONS

As discussed in Section 2, there is a family of space weather missions that have yet to be realized without the ability to take simultaneous measurements of a phenomenon over a large volume. One such mission is the detection and mapping of plasma bubbles or ionospheric plasma depletions that cause satellite communication outages when these depletions disrupt or scintillate the signal, as depicted in Figure 13. Such missions will have impact on commercial, government, and military sectors which all depend on satellite communications for commerce, political stability, and military operations.

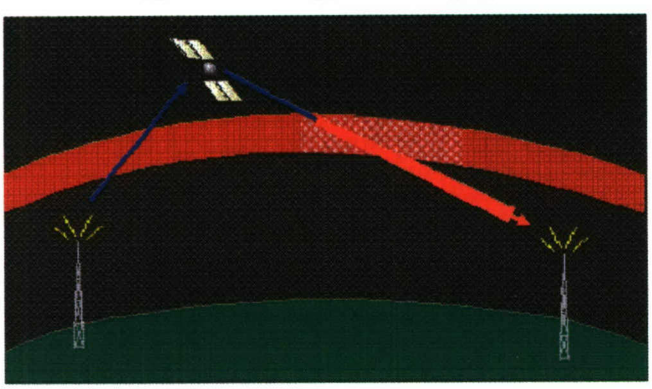

Figure 13. Satellite Communication Signal Scintillation

From an industrial perspective, where commercial applications of small spacecraft are only just appearing, there is a tendency towards growth in spacecraft size, mass and complexity in order to mitigate risk and meet commercial requirements. The benefits of a distributed constellation approach, where individual spacecraft can be made smaller and missions risk is spread across a cluster is attractive. This must be weighed against limits particularly in aperture size, which mean that very small spacecraft struggle to perform some of the near commercial missions such as frequent revisit Earth imaging, which are currently the largest market driver.

The next phase of this project is to develop the space segment and architecture for a dual mission to study plasma depletions and the drag environment. The Miniature Electrostatic Analyzer (MESA) has been identified as a candidate payload for the scintillation study [61]-[62]. MESA has already been designed, built, and tested in plasma environments in terrestrial test chambers back in 2002. MESA was integrated with FalconSAT-2, which was destroyed during launch in 2005 [63]. Work has progressed since that time to further miniaturizing the sensor, making it possible for integration with the ES-Femto project, as it has a mass of only a few grams and requires very little power, which would already fit within the ES-Femto EPS budget. The data rate requirements are also very low, suitable for the 115.2 kbps wireless comm. links. The MESA sensor is shown in Figure 14.

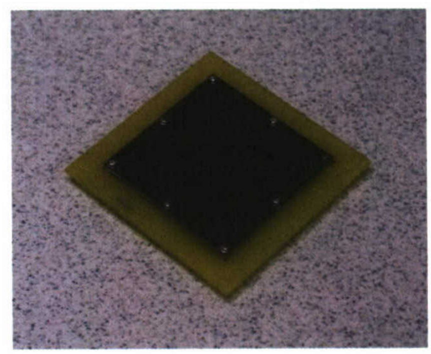

Figure 14. USAF Academy Developed MESA Sensor

An ultra-sensitive accelerometer has been considered as the key payload for the drag environment monitoring [64]. It is not yet certain if the device can be made available for this project.

The mission architecture will also need to be developed, as there are many issues yet to be solved. Similar to the SMAD mission architecture, the U.S DoD Architecture Framework is being considered for the template [65]. A key part of the architecture is a co-orbiting nano- or microsatellite data relay.

The final system configuration is envisioned to be a 10x10x2 cm block as shown in Figure 15. It would be designed to be compatible with the existing PPOD launcher, where 15 ES-Femtos could be jettisoned from each PPOD [51].

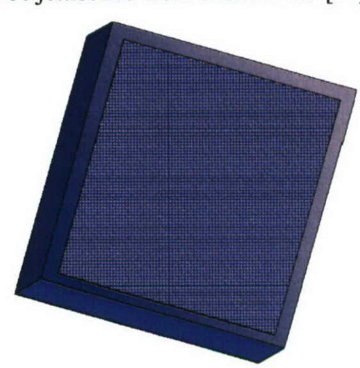

Figure 15. Conceptual Final Design of ES-Femto

6.2 SPIN-OFF APPLICATIONS

The possibility of spin-off applications was identified early in the project. Due to the author's continued support of the EyasSAT project managed by the USAF Academy, it was realized that by accepting certain design constraints, that this project could benefit EyasSAT in three tangible ways. The most important spin-off was the ability to offer a payload module option for EyasSAT, which currently does not exist. The EyasSAT project has always had a goal of encouraging student built payloads and subsystems to be created by the user community. Since no one else has yet stepped up to the challenge, publicizing this development will hopefully encourage students at other universities to build one. The University of Surrey is currently investigating the possibility of integrating student-built payloads and subsystems for EyasSAT into their space-related undergraduate and graduate programs [54].

Another spin-off application with much less widespread impact are the lessons learned in the latest COTS components, improved EPS designs, and GPS technologies. These lessons can be applied to the next EyasSAT design, which is currently in progress. In addition, ES-Femto can potentially be used as a very low-cost option to EyasSAT to address markets where institutions cannot afford a complete EyasSAT system.

7. CONCLUSIONS

A new class of DSMs is emerging which requires hundreds to thousands of satellites to accomplish long-awaited remote sensing and science mission objectives. These missions, stymied by the lack of a low-cost mass-producible solution, can become reality by merging the concepts of DSSs and terrestrial WSNs. However, unlike terrestrial WSN nodes, DSS nodes must survive the unique hazards of the space environment whilst undergoing complex orbital dynamics. A novel sub-kilogram VSS design is required.

This paper was presented with a problem-solution approach. The problem or challenge in this case, is the fact that numerous envisaged DSMs with great benefit to society are waiting for technical solutions to be developed. Most of the academic excitement currently surrounds a few missions that require small clusters of formation flying satellites, each being very complex. The problems yet to be solved associated with formation flying are numerous and each very challenging. In contrast, there are numerous beneficial missions that rely on less complex architectures based on traditional satellite constellations to achieve real-time, distributed, multi-point sensing. However, these architectures require hundreds to thousands of low-cost, mass-producible satellite nodes.

An initial prototype of a femtosatellite has been designed, built, and tested successfully using commonly available commercial practices at a unit cost of $300. The first two designs of ES-Femto are clearly focused on function and performance. The next step is to focus on the selected ionospheric plasma depletion mission to study to enhance our understanding of scintillation on communication links through the atmosphere. Meeting mission requirements, solving the space environment problems, and developing a mission architecture are the remaining challenges. It is estimated that the per node cost will not exceed $1000 and the system will able to be deployed with existing launch vehicle interfaces.

ACKNOWLEDGEMENTS

The views expressed in this article are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government. Cleared for public release, distribution unlimited. U.S. (Air Force Institute of Technology PA #TBD).

REFERENCES

[1] K. Romer and F. Mattern, "The Design Space of Wireless Sensor Networks," *IEEE Wireless Communications*, vol. 11, no. 6, December 2004, pp. 54-61.

[2] D. J. Barnhart, T. Vladimirova, and M. N. Sweeting, "Satellite-on-a-Chip: A Feasibility Study," in *Proc. 5th Round Table on Micro/Nano Technologies for Space*, Nordwijk, 2005.

[3] D. J. Barnhart, T. Vladimirova, and M. N. Sweeting, "Satellite-on-a-Chip Development for Future Distributed Space Missions," in *Proc. CANEUS Conference on Micro-Nano Technologies for Aerospace Applications*, Toulouse, France, Paper CANEUS2006-11045.

[4] C. D. Jilla and D. W. Miller, "Multi-Objective, Multidisciplinary Design Optimization Methodology for Distributed Satellite Systems," *Journal of Spacecraft and Rockets*, vol. 41, no. 1, January–February 2004, pp. 39-50.

[5] R. Burns, C. Cheung, G. Davis, E. Cary, J. Higinbotham, and K. Hogie, "A System for Real-Time, Closed-Loop, Multi-Spacecraft Mission Simulation Applications," in *Proc. AIAA Modeling and Simulation Technologies Conference and Exhibit*, Austin, TX, 2003, Paper AIAA-2003-5381.

[6] G. B. Shaw, D. W. Miller, and D. E. Hastings, "Generalized Characteristics of Communication, Sensing, and Navigation Satellite Systems," *Journal of Spacecraft and Rockets*, vol. 37, no. 6, November-December 2000, pp. 801-811.

[7] T. P. Garrison, M. Ince, J. Pizzicaroli, and P. A. Swan, "Systems Engineering Trades for the IRIDIUM® Constellation," *Journal of Spacecraft and Rockets*, vol. 34, No. 5, September—October 1997, pp. 675-680.

[8] R. Peters, "Commercial Inter-Satellite Links, What Happened?" in *Proc. 21st International Communications Satellite Systems Conference and Exhibit*, Yokohama, Japan, 2003, Paper AIAA-2003-2325.

[9] A. da Silva Curiel, "Small Satellite Constellations for Earth Observation," in *Proc. 55th International Astronautical Congress*, Vancouver, Canada, 2004, Paper IAC-04-IAA.4.11.4.08.

[10] F. Serene and N. Corcoral, "PARASOL and CALIPSO: Experience Feedback on Operations of Micro and Small Satellites," in *Proc. SpaceOps 2006 Conference*, Rome, 2006, Paper AIAA-2006-5919.

[11] J. Ray, "Tiny Probes Launched to Test Advanced Technologies," *Spaceflight Now*, March 22, 2006 [Online]. Available: http://www.spaceflightnow.com/pegasus/st5/

[12] C. Fong, B. Wu, N. Yen, and P. Chen, "Application of FORMOSAT-3/COSMIC Mission to Global Earth Monitoring," in *Proc. AIAA Space 2005*, Long Beach, CA, 2005, Paper AIAA-2005-6774.

[13] E. Ashford, "Non-Geo Systems...where have all the Satellites Gone?" in *Proc. 54th International Astronautical Congress*, Bremen, 2003, Paper IAC-03-M.4.01.

[14] S. Norris, "Commercial Applications for Microsatellites," in *Proc. AIAA Space 2001*, Albuquerque, NM, 2001, Paper AIAA-2001-4743.

[15] C. Edery-Guirardo, J.P. Aguttes, E. Bouisson, and F. Forestier, "Small Relay Satellites for Improving the Reactivity of

Observation Satellites," in *Proc. 54th International Astronautical Congress*, Bremen, 2003, Paper IAC-03-B.2.04.
[16] E. Lagier and D. Craig, "JAMFEST - A Cost Effective Solution to GPS Vulnerability Testing," in *Proc. USAF Developmental Test and Evaluation Summit*, Woodland Hills, CA, 2004, Paper AIAA-2004-6853.
[17] M. Bille, R. Kane, M. Nowlin, "Military Microsatellites - Matching Requirements and Technology," in *Proc. AIAA Space 2000*, Long Beach, CA, 2000, Paper AIAA-2000-5186.
[18] M. N. Sweeting, "Shaping the Future," *University of Surrey Annual Report 2004/2005*, p. 5, [Online]. Available: http://portal.surrey.ac.uk/pls/portal/docs/PAGE/GATEWAY/CORPORATE/ANNUAL%20REPORT%20UNIVERSITY%20OF%20SURREY_0.PDF
[19] A. Das, R. Cobb, M. Stallard, "Techsat 21 - A Revolutionary Concept in Distributed Space-based Sensing," in *Proc. AIAA Defense and Civil Space Programs Conference and Exposition*, Huntsville, AL, 1998, Paper AIAA-1998-5255.
[20] J. G. Macke, D. P. Miller, M. A. Swartwout, K. J. Bennett, and W. D. Smart, "Deployable Inspector Spacecraft for Distributed Field Measurements," in *Proc. 22nd AIAA International Communications Satellite Systems Conference and Exhibit*, Monterey, CA, 2004, Paper AIAA-2004-3152.
[21] F. A. Herrero, M. DiJoseph, T. E. Moore, J. A. Slavin, and R. Vondrak, "NanoSat Constellations for Geospace Science," in *Proc. AIAA Space 2000*, Long Beach, CA, Paper AIAA-2000-5174.
[22] W. T. Huntress, "Statement of NASA to Congress," Subcommittee on Space and Aeronautics, Committee on Science, U.S. House of Representatives, April 1997.
[23] L. H. Krause, C. L. Enloe, R. K. Haaland, and P. Golando, "Microsatellite Missions to Conduct Midlatitude Studies of Equatorial Ionospheric Plasma Bubbles," *Advances in Space Research*, vol. 36, no. 12, 2005, pp. 2474-2479.
[24] G. Blackwood, C. Henry, E. Serabyn, S. Dubovitsky, M. Aung, and S. Gunter, "Scope and Objectives of the Terrestrial Planet Finder Interferometer Study," in *Proc. AIAA Space 2003*, Long Beach, CA, 2003, Paper AIAA-2003-6329.
[25] P. Ferguson, F. Busse, B. Engberg, J. How, M. Tillerson, N. Pohlman, A. Richards, and R. Twiggs, "Formation Flying Experiments on the Orion-Emerald Mission," in *Proc. AIAA Space 2001*, Albuquerque, NM, 2001, Paper AIAA-2001-4688.
[26] J. Carpenter, J. Leitner, D. Folta, and R. Burns, "Benchmark Problems for Spacecraft Formation Flying Missions ," in *Proc. AIAA Guidance, Navigation, and Control Conference and Exhibit*, Austin, TX, 2003, Paper AIAA-2003-5364.
[27] Surrey Satellite Technology Limited, "Small Satellites Home Page," [Online]. Available: http://centaur.sstl.co.uk/SSHP/index.html
[28] C. I. Underwood, G. Richardson, and J. Savignol, "SNAP-1: A Low Cost Modular COTS-Based Nano-Satellite – Design, Construction, Launch and Early Operations Phase," in *Proc. 15th Annual AIAA/USU Conference on Small Satellites*, Logan, UT, 2001, Paper SSC01-V-1a.
[29] F. Bruhn, J. Köhler, and L. Stenmark, "NanoSpace-1: the Impacts of the First Swedish Nanosatellite on Spacecraft Architecture and Design," in *Proc. 53rd International Astronautical Congress*, Houston, TX, 2002, Paper IAC-02-U.4.01.
[30] F. Bruhn and L. Stenmark, "NanoSpace-1: Spacecraft Architecture and Design after Concluding Phase B," in *Proc. 5th Round Table on Micro/Nano Technologies for Space*, Nordwijk, 2005.
[31] M. Hapgood, S. Eckersley, R. Lundin, M. Kluge, U. Prechtel, P. Hyvönen, "Nano Satellite Beacons for Space Weather Monitoring," in *Proc. 5th Round Table on Micro/Nano Technologies for Space*, Nordwijk, 2005.
[32] V. Srinivasan, "Students Launch OPAL Satellites," The Stanford Daily, 17 February 2000 [Online]. Available: http://www.stanforddaily.com/tempo?page=content&id=2171&repository=0001_article
[33] Clyde Space Ltd., "CubeSat Power: A Power System for Miniature Spacecraft," [Online]. Available: http://www.clyde-space.com/Cubesat_Power.html
[34] C. I. Underwood, V. J. Lappas, A. da Silva Curiel, M. Unwin, A. M. Baker, and M. N. Sweeting, "Using PALMSAT Pico-Satellite Technologies to Meet Mission Scenarios," in *Proc. 55th International Astronautical Congress*, Vancouver, Canada, 2004, Paper IAC-04-P.5.A.01.
[35] Cyrospace, Inc., "Femtosatellite is the smallest operational satellite ever built," [Online]. Available: http://www.cyrospace.com/products/pdfs/CyroBro_SS.pdf
[36] H. Helvajian and S. W. Janson, "The Fabrication of a 100 gm Co-Orbiting Satellite Assistant (COSA) Using Glass Ceramic Materials And 3-D Laser Processing Techniques," in *Proc. 9th International Micromachine/Nanotech Symposium*, Tokyo, Japan, 2003, pp. 33-41.
[37] J. Keller interview of A. Joshi, "Startup to Develop Satellite-On-A-Chip," *Military & Aerospace Electronics*, February 1994 [Online]. Available: http://www.chipsat.com/press/press01.php
[38] S. W. Janson, H. Helvajian, S. Amimoto, G. Smit, D. Mayer, and S. Feuerstein, "Microtechnology for Space Systems," in *Proc. 1998 IEEE Aerospace Conference*, Big Sky, MT, vol. 1, 1998, pp. 409–418.
[39] H. Helvajian, *Microengineering Aerospace Systems*, Reston, VA, AIAA Press, 1999.
[40] S. W. Janson, H. Helvajian, and K. Breuer "MEMS, Microengineering and Aerospace Systems," in *Proc. 30th AIAA Fluid Dynamics Conference*, Norfolk, VA, 1999, Paper AIAA-1999-3802.
[41] S. W. Janson, "Mass-Producible Silicon Spacecraft for 21st Century Missions," in *Proc. AIAA Space 1999*, Albuquerque, NM, 1999, Paper AIAA-1999-4458.
[42] S. W. Janson, "Nanotechnology - Tools for the Satellite World," *Keynote Address, 6th ISU Annual International Symposium*; "Smaller Satellites, Bigger Business?", Strasbourg, France, 2001, pp.21-30.
[43] S. W. Janson, "Micro/Nanotechnology for Micro/Nano/Picosatellites," in *Proc. AIAA Space 2003*, Long Beach, CA, 2003, Paper AIAA-2003-6269.
[44] S. Janson, A. Huang, W. Hansen, L. Steffeney, and H. Helvajian, "Development of an Inspector Satellite Using Photostructurable Glass/Ceramic Materials," in *Proc. AIAA Space 2005*, Long Beach, CA, 2005, Paper AIAA-2005-6802.
[45] L. Xuwen, L. Li, L. Huawang, C. Yinjian, S. Dexin, and Y. Genqing, "Silicon Solid-state Small Satellite Design Based on IC and MEMS," in *Proc. 1998 5th International Conference on Solid-State and Integrated Circuit Technology*, Beijing, 1998, pp. 932-935.
[46] R.J. Shul, S.H. Kravitz, T.R. Christenson, C.G. Willison, T.E. Zipperian, "Silicon Microfabrication Technologies for Nano-satellite Applications," in *Proc. ASCE Space 2000: The Seventh International Conference and Exposition on Engineering, Construction, Operations, and Business in Space*, Albuquerque, NM, 2000, pp. 482-487.
[47] B. Jackson and K. Epstein, "A Reconfigurable Multifunctional Architecture Approach for Next-Generation Nanosatellite Design," in *Proc. 2000 IEEE Aerospace Conference*, Big Sky, MT, vol. 7, 2000, pp. 185-193.
[48] K. Miller, C. Mogensen, and T. Gillespie, "Innovative, Low Cost Microspacecraft," in *Proc. AIAA Space 2000*, Long Beach, CA, 2000, Paper AIAA-2000-5196.
[49] T. Mosher and B. Stucker, "Responsive Space Requires Responsive Manufacturing-Part II," in *Proc. AIAA Space 2004*, San Diego, CA, 2004, Paper AIAA-2004-6117.

[50] M. Pimprikar and T. George, "CANEUS NPS (Nano-Pico-Satellites) Inc. to Develop the World's Most Advanced Miniature Satellites," [Online]. Available: http://www.caneus.org/CANEUS06/CANEUS_NPS.ppt

[51] I. Nason, J. Puig-Suari, R. Twiggs, "Development of a Family of Picosatellite Deployers Based on the CubeSat Standard," in *Proc. 2002 IEEE Aerospace Conference*, Big Sky, MT, vol. 1, 2000, pp. 1-457 - 1-464.

[52] Barnhart, D. J, Ritchey, O. NG, Sellers, J. J, White, J. J, White, T. L, Clark, J. B, "EyasSAT: Transforming the Way Students Experience Space Systems Engineering," in *Proc. 2004 ASEE Annual Conference & Exposition Proceedings*, Salt Lake City, UT, 2004.

[53] D. J. Barnhart, J. J. Sellers, C. A. Bishop, J. R. Gossner, J. J. White, J. B. Clark, "EyasSAT: A Revolution in Teaching and Learning Space Systems Engineering," in *Proc. AIAA Space Systems Engineering Conference*, Atlanta, GA, November 2005.

[54] D. J. Barnhart, T. Vladimirova, A. Ellery, C. I. Underwood, "Utilising the EyasSAT Concept in Space Systems Engineering Courses at the University of Surrey," in *Proc. International Astronautics Congress*, Valencia, Spain, 2006, Paper IAC-06-E1.4.04.

[55] J. R. Wertz and W. J. Larson, *Space Mission Analysis and Design*, 3rd Edition, El Segundo, CA, Microcosm Press, 1999.

[56] T. P. Sarafin, *Spacecraft Structures and Mechanisms*, El Segundo, CA and The Netherlands, Microcosm and Kluwer Publishing, 1995.

[57] Maxim Integrated Products, "Harnessing Solar Power with Smart Power-Conversion Techniques," Application Note 484, [Online]. Available: http://www.maxim-ic.com/appnotes.cfm/appnote_number/484

[58] H. Zhang, C. Yang, and Z. Qiu, "The GPS Receiver for Micro/Nanosatellites," in *Proc. NanoTech 2002 - "At the Edge of Revolution"*, Houston, TX, 2002, Paper AIAA-2002-5753.

[59] M. L. Psiaki, "Nanosatellite Attitude Stabilization Using Passive Aerodynamics and Active Magnetic Torquing," *Journal of Guidance, Control, and Dynamics*, vol. 27, no. 3, May 2004, pp. 347-355.

[60] T. Williams and Z-S. Wang, "Potential Non-propulsive Stationkeeping Techniques for Picosatellite Formation Flight," in *Proc. AIAA/AAS Astrodynamics Specialist Conference*, Denver, CO, 2000, AIAA-2000-4134.

[61] C. L. Enloe, L. H. Krause and R. K. Haaland, "Miniaturized Electrostatic Analyzer Manufactured Using Photolithographic Etching," *Review of Scientific Instruments*, vol. 74, no. 3, 2003, pp. 1192-1195.

[62] L. H. Krause, C. L. Enloe, R. K. Haaland, and P. Golando, "Microsatellite Missions to Conduct Midlatitude Studies of Equatorial Ionospheric Plasma Bubbles," *Advances in Space Research*, vol. 36, no. 12, 2005, pp. 2474-2479.

[63] L. H. Krause, C. L. Enloe, R. K. Haaland, "Fast In-Situ Measurements of Ionospheric Plasma with the Miniature Electrostatic Analyzer (MESA): An Experiment Aboard FalconSAT-2," in *Proc. 2002 IEEE Aerospace Conference Proceedings*, vol. 2, 2002, pp. 2-631 - 2-639.

[64] F. T. Hartley, "Development and Terrestrial Applications of a Nano-g Accelerometer," *Proceedings of the SPIE—Electronics and Structures for MEMS*, vol. 3891, September 1999, pp. 410-415.

[65] DoD Architecture Framework Working Group, "DoD Architecture Framework Version 1.0," vol. 1, 9 February 2004. Available: http://www.defenselink.mil/nii/doc/DoDAF_v1_Volume_I.pdf